Surface-acoustic-wave-driven luminescence from a lateral p-n junction

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The authors report surface-acoustic-wave-driven luminescence from a lateral p-n junction formed by molecular beam epitaxy regrowth of a modulation doped GaAs/AlGaAs quantum well on a patterned GaAs substrate. Surface acoustic wave driven transport is demonstrated by peaks in the electrical current and light emission from the GaAs quantum well at the resonant frequency of the transducer. This type of junction offers high carrier mobility and scalability. The demonstration of surface acoustic wave luminescence is a significant step towards single-photon applications in quantum computation and quantum cryptography.

Surface acoustic waves (SAWs) travelling on a piezoelectric material containing a buried layer of charge have attracted significant interest in recent years.[1,2,3] In particular it has been shown that the associated electrostatic wave can be used to transport single electrons through a split gate leading to a quantised current.[4] This effect led to the proposal of a single-photon source in which the SAW is used to pump single electrons across a lateral p-n junction.[5] In this proposal the photon emission time coincides with the arrival of each SAW minimum, creating a high repetition rate single-photon source ideal for use in quantum cryptography. Barnes *et al.* have proposed a computation scheme where information is stored in the spin of an electron propagating in a SAW minimum.[6] Single-qubit and two-qubit operations would be performed as the electrons are carried through a series of magnetic and non-magnetic gates. Our device could act as an optical readout for this scheme with quantum information transferred from the electron spin to the polarization of the emitted photons.[7]

The first step towards such a single-photon source is the demonstration of SAW-mediated transport across a lateral p-n junction and the resulting luminescence. Several types of lateral junctions have been investigated so far.[8,9,10,11] In this letter we present results from a lateral p-n junction in a GaAs/AlGaAs modulation doped quantum well formed by molecular beam epitaxy regrowth on a patterned GaAs wafer.[12,13,14] The amphoteric nature of silicon enables n-doped material to be grown on the flat (100) GaAs substrate and p-doped material to be grown on etched (n11)A facets (for n$\leq$3) in the same growth step.[15] A lateral p-n junction is formed at the interface between the flat and etched planes. Prior to growth the (100) GaAs substrate was patterned with stripes parallel to the $[1\bar{1}0]$ direction using 18:11:180

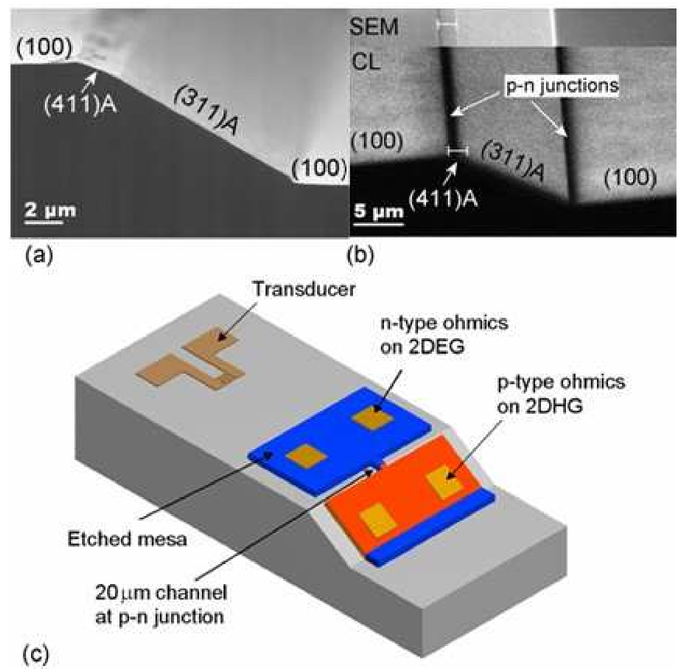

FIG. 1: (a) Scanning electron microscope image (SEM) showing a cross-section through the wafer after re-growth. p-n junctions form at the interfaces between the planes. (b) Panchromatic cathodoluminescence (CL) image at room temperature taken at an oblique angle. Inset: SEM image for comparison. (c) Schematic diagram of the device.

BHF:H_2O_2:H_2O solution at 10°C. This etch exposes $\sim$ 25° facets to the (100) surface, as shown in Figure 1a, creating a (100)-(311) A-(100) step. The photoresist is removed by a series of solvent rinses and an oxygen plasma etch before the wafer is transferred to the MBE system and cleaned in-situ by exposure to a hydrogen radical beam.[16] The growth consisted of a 5.5×10^{11} cm^{-2} Si delta doped layer to counteract the effects of residual surface contamination,[16] a 100 nm $Al_{0.33}Ga_{0.66}As$ buffer layer, a 500 nm (2.5 nm $Al_{0.33}Ga_{0.66}As$/ 2.5 nm

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GaAs) superlattice barrier, a 15 nm GaAs quantum well, a 40 nm $Al_{0.33}Ga_{0.66}As$ spacer, a 40 nm $1.1 \times 10^{18}\,cm^{-3}$ Si doped $Al_{0.33}Ga_{0.66}As$ region and a 14 nm GaAs cap. The GaAs growth rate was 1 μm/hour, the substrate temperature was 600°C and the V/III beam equivalent pressure ratio was 7.4. This forms a 2D lateral n-p-n junction with a high mobility two-dimensional electron gas (2DEG) on the top plane (carrier density of $3.4 \times 10^{11}\,cm^{-2}$ and mobility of $4.9 \times 10^{5}\,cm^{2}/Vs$ measured at 1.5 K after illumination with a red light emitting diode) and a two-dimensional hole gas (2DHG) on the (311) A facet. Figure 1a also shows an additional (411) A facet formed at the top (100)-(311) A junction during the overgrowth. Figure 1b shows a room temperature panchromatic cathodoluminescence image of the structure. The positions of the p-n junctions at the top and bottom of the facet show up as dark lines. In these regions the high electric field sweeps the carriers away before they are able to recombine. The width of these lines can be used to estimate the depletion regions of the unbiased junction as $\sim 1\,\mu$m.

Devices were fabricated on this wafer as shown in Figure 1c. Although the wafer has a p-n junction at both the top and bottom of the facet all measurements were carried out on the top junction as this allowed better lithographic resolution. Standard optical lithography was used to pattern a mesa giving a 20 μm wide channel across the top p-n junction. AuBe p-type contacts were made to the 2DHG and AuGeNi n-type contacts to the top 2DEG. An interdigital transducer with a resonant frequency of approximately 984 MHz was placed 2.2 mm away from the junction on an etched region of the top plane. The device was bonded into a package designed to provide some shielding from the free-space electromagnetic (EM) wave radiating from the transducer circuit. Measurements were carried out in a liquid helium continuous flow cryostat with a base temperature of 4 K. The actual device temperature is not well known, as the microwave coaxial cables used to apply radio-frequency (RF) signals to the transducer will cause some heating. The light emitted was collected through a microscope objective lens and spectrally recorded with a grating spectrometer and nitrogen cooled charge coupled device (CCD).

The electrical characteristics of several diodes were studied without the presence of a SAW. They showed the expected rectifying behavior with negligible reverse-bias current (< 10 pA in the range 0 to -2 V) and at a fixed forward bias voltage the current through the device was stable.

Figure 2a shows the emission from one device for a range of forward bias conditions. The peak at 806 nm and the broad peak at longer wavelength are attributed to emission from the GaAs quantum well. The quantum well is nominally 15 nm wide but there will be some lateral variation in the width due to the differences in the growth rates on different crystallographic planes. In particular the quantum well should be narrower on the

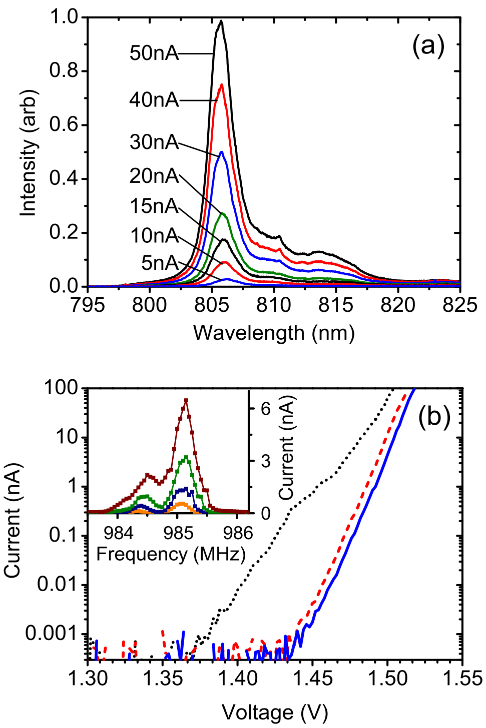

FIG. 2: (a) Electroluminescence spectra for a range of bias current (5–50 nA) with no SAW present. (b) IV-characteristics of the p-n junction. Solid line (blue): no power applied to the transducer, dotted line (black): 12 dBm applied at the transducer's resonant frequency, dashed line (red): 12 dBm applied off-resonance. The inset shows the frequency dependence of the current for a range of bias voltages (1.42–1.45 V).

angled (311) A facets since the incident Ga flux is about 90% of that on the perpendicular (100) planes. The Ga adatom diffusion length is also longer on the (311) A facets than on the (100) planes, leading to the buildup of material and the formation of extra (411) A and (111) A facets at the top and bottom interfaces respectively.[17,18] Both of these effects will cause the quantum well width to vary across the p-n junction, so the wavelength of the emitted photons will depend on the exact position of the recombination. Emission was seen at the top of the facet across the width of the 20 μm channel, but the intensity and exact form of the spectra varied across the channel. This is not unexpected as there are some irregularities in the facet caused by unevenness in the pre-regrowth etch and there are likely to be associated fluctuations in the well width. The position of the peak at 806 nm is seen to decrease slightly in wavelength at higher bias voltages.

With no SAW present the diode characteristic of this device was exponential (Figure 2b solid line). However, the presence of the SAW changed the IV-curve dramatically (Figure 2b dotted line). This effect was not seen

when the transducer was driven off-resonance (Figure 2b dashed line) indicating that it is due to SAW-mediated transport across the junction. There is a small increase in the current off-resonance, which might be caused by heating of the diode or modulation of the junction by the free-space EM wave but it is insignificant compared to the effect of the SAW generated on-resonance. The inset in Figure 2b shows the change in the current as a function of transducer frequency. The oscillations are caused by interference between the main SAW and a reflected SAW or the free-space EM wave.[19] It can be seen from Figure 2b that below a certain bias voltage there is no SAW-driven current. This is expected as the electric field of the unbiased junction (1.5 V dropped across the depletion width of $\sim 1\,\mu$m) is too large for the SAW (wavelength 3 μm, amplitude of a few 10s of mV) to transport electrons across the junction.[20,21] Subsequent measurements were taken when the diode was forward biased to below threshold (where negligible light emission was observed) but the potential slope was shallow enough for the SAW to carry electrons across the junction. Over time the resonant frequency of the transducer decreased approximately linearly. It is thought that this is due to mass loading of the transducer as residual gases in the cryostat condensed on the cold sample.[22] Although this shift is not important it means that the exact frequency dependence of measurements taken at different times cannot be compared.

Figure 3a shows the luminescence from the junction as a function of the frequency applied to the transducer. The peak in the emission occurs at the resonant frequency of the transducer where a SAW is generated. This associates the luminescence with the SAW as the pick-up from the free-space EM wave is not strongly frequency dependent.[23] Away from the resonant frequency of the transducer there is no light emission observed above the background. The luminescence is dominated by emission from the quantum well showing that the carriers are confined in the well across the whole width of the junction and that there are no other radiative paths. The peak emission occurs at ~ 805.5 nm, slightly lower than seen in the electroluminescence measurements. The majority of the SAW-driven light was localized across a small region corresponding to a visible irregularity in the facet caused by the pre-regrowth etch. Figure 3b shows the integrated intensity of the light emitted as a function of transducer frequency. The oscillations are due to the same interference effect as observed in the current traces.

In summary, we have fabricated a high mobility lateral diode by MBE regrowth and shown emission from the 15 nm quantum well. SAW-driven electron transport across the junction has been demonstrated by an increase in both the current through and luminescence from the junction at the resonant frequency of the transducer. This device could be used for optical readout or information transfer in a quantum computation scheme and is the first step towards realizing an acousto-electrically driven single-photon source for high frequency operation.

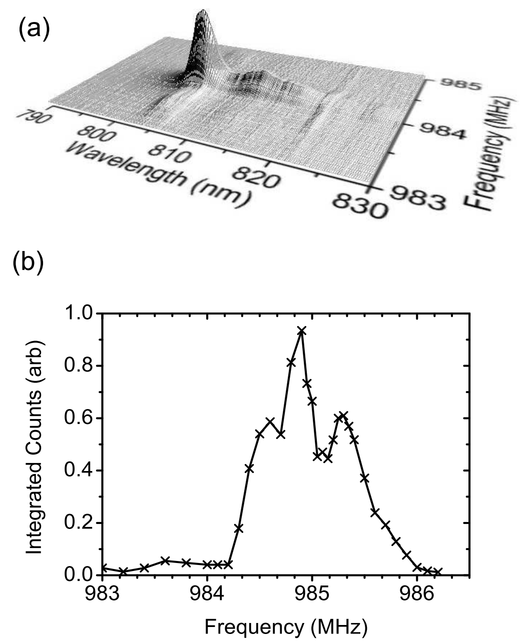

FIG. 3: (a) SAW-driven luminescence as a function of the frequency applied to the transducer (12 dBm). The diode was d.c. biased to 1.47 V. (b) Integrated light intensity at 1.47 V, with a transducer power of 12 dBm as a function of the frequency applied to the transducer.

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